Modeling the Future

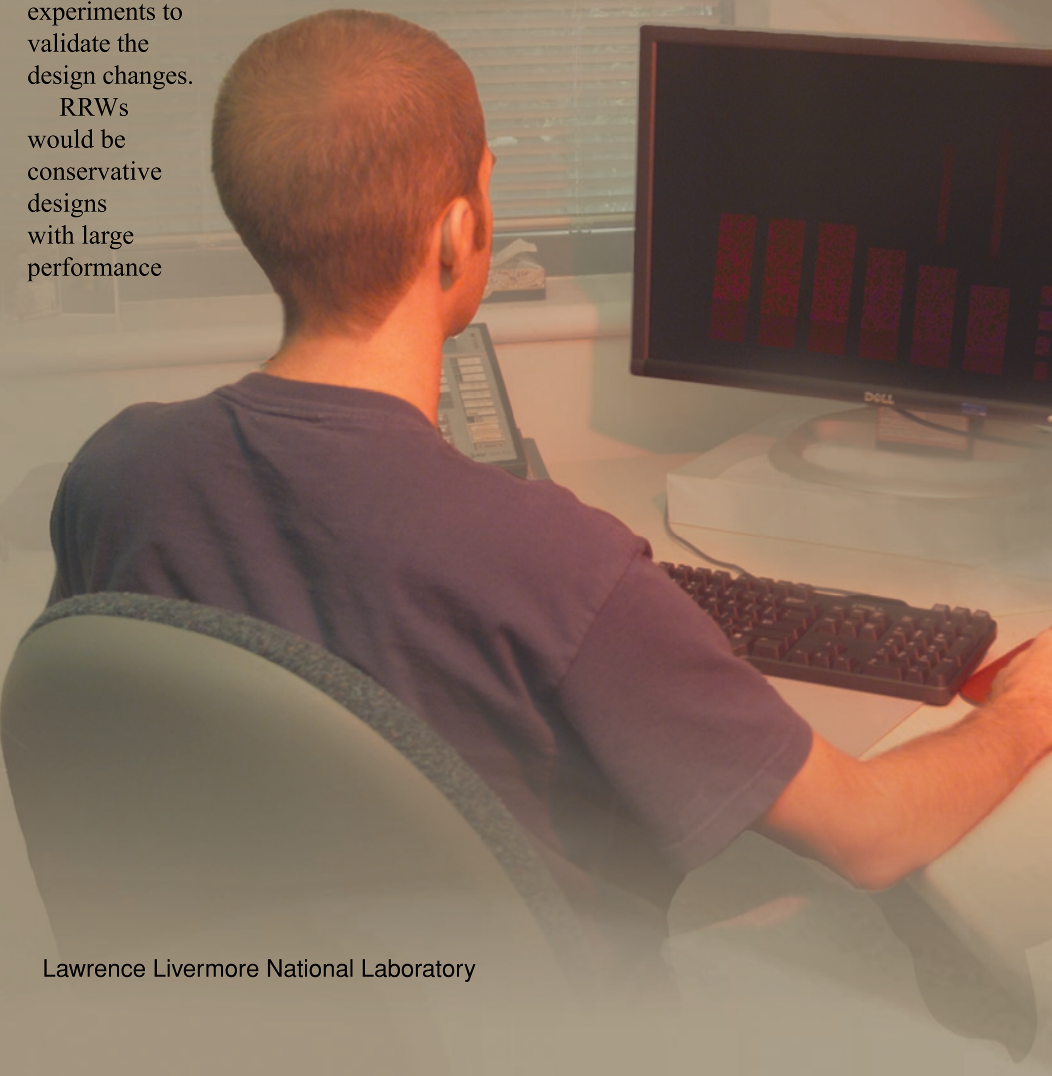
A computational tool aims to help the U.S. create a responsive nuclear enterprise.

NUCLEAR weapons have been a cornerstone of U.S. national security since the early 1950s. As the nation adapts to the security threats of the 21st century, the role of these weapons is changing, as is the large nuclear complex, or enterprise, that was built to research, produce, and maintain them. A series of top-level studies and reviews at the Department of Energy (DOE), its National Nuclear Security Administration (NNSA), and the Department of Defense (DoD) has called for a smaller, more agile nuclear enterprise—one that can respond quickly to a sudden change in the geopolitical environment or a discovery of an acute technical problem in the nuclear stockpile. (See the box on p. 9.)

NNSA Administrator Linton Brooks says his goal is to have a "responsive nuclear enterprise that is resilient to unanticipated events or emerging threats." This need becomes particularly important as the stockpile is reduced in accordance with the Moscow Treaty, which was signed in 2001. Brooks and other analysts note that the current stockpile was developed to counter the threat posed by the Soviet Union, the nation's principal adversary during the Cold War. Weapon scientists designed warheads to maximize the yield-to-weight ratio so a missile or bomber could carry more than one. During the Cold War, aging warheads were regularly replaced when new designs became available, but today, no new ones are being developed. The current stockpile is being maintained past its planned lifetime, and certifying the performance and reliability of these weapons is becoming a more difficult and costly challenge.

Nuclear weapons experts are considering several options to create the modern nuclear enterprise. For example, with the support of Congress, NNSA has begun the Reliable Replacement Warhead (RRW) Program. The program's goal is to determine whether the U.S. could replace aging warheads with ones that are more easily manufactured and cheaper to maintain, without needing to conduct nuclear experiments to validate the design changes.

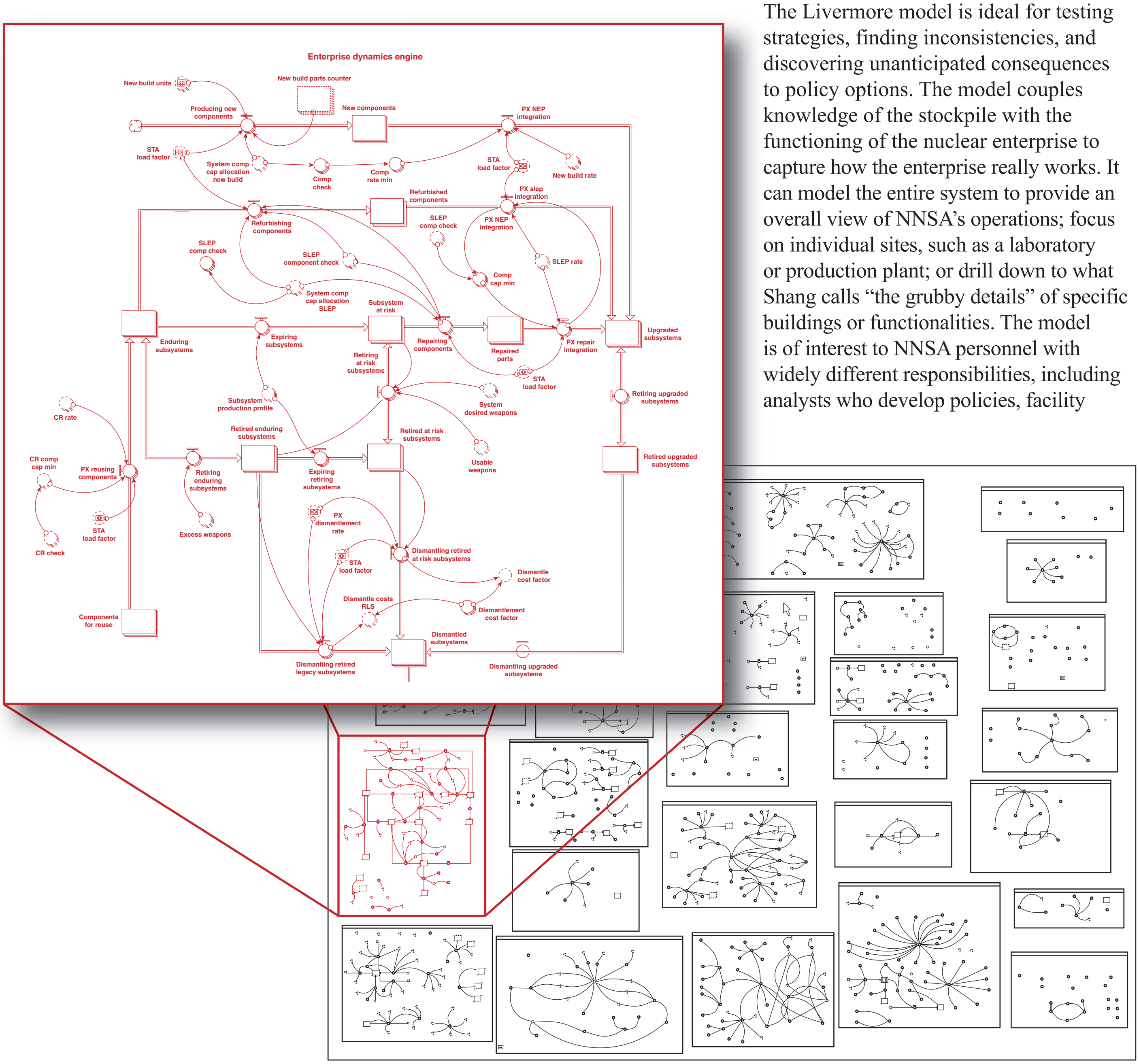
RRWs would be conservative designs with large performance margins within the design parameters validated by past nuclear data, which are important for reliability. They also would include better safety and security features. The program requires that RRW designs remain within the military requirements of the existing stockpile as well as the test-validated parameters. Production of RRWs is intended to reduce the need for a sizable secure reserve and could lead to a stockpile with substantially fewer warheads.



To help NNSA and individual sites evaluate such options, Cliff Shang, a physicist in Livermore's Defense and Nuclear Technologies Directorate, has developed a complex, classified tool to model the nuclear enterprise. The code goes beyond the spreadsheets and isolated studies typically used in planning exercises. Instead, it takes a computational physics approach, using differential equations tied to a large database to simulate proposed changes.

Ideal for Testing Strategies

"We're developing more quantitative tools to assist decision makers," says Shang. The Livermore model is ideal for testing strategies, finding inconsistencies, and discovering unanticipated consequences to policy options. The model couples knowledge of the stockpile with the functioning of the nuclear enterprise to capture how the enterprise really works. It can model the entire system to provide an overall view of NNSA's operations; focus on individual sites, such as a laboratory or production plant; or drill down to what Shang calls "the grubby details" of specific buildings or functionalities. The model is of interest to NNSA personnel with widely different responsibilities, including analysts who develop policies, facility



The Livermore model of the nuclear weapons complex, or enterprise, takes a computational physics approach to analyze planning options. Shown to the right is one-third of the logic diagrams that connect the differential equations describing the operations of the National Nuclear Security Administration's (NNSA's) enterprise. Above, a set of logic diagrams reveals the rich detail of warheads and components described by the equations.

managers who are concerned with building maintenance schedules, budget experts who track staffing projections, and transportation managers who are charged with delivering dismantled warhead components to the appropriate sites on schedule.

For example, the model allows users to view how fast the enterprise could respond, and in what ways, if requirements changed suddenly to address a geopolitical situation. It can also predict the effect that a severe technical problem might have on an NNSA program, and it can compare how levels of investments in the infrastructure will affect the responsiveness of the nuclear enterprise as a whole.

"Data by themselves are interesting, but they do not always show the big picture," says Shang. "With our model, we can see realistic results to questions and hypotheses." He notes that the model can help managers avoid making decisions that negatively affect seemingly unrelated processes. "We can change one element in a calculation and watch how it affects others. Isolated solutions may have unintended ripple effects, whether positive or negative." One simulation showed that consolidating nuclear material in fewer buildings not only streamlined production operations but also simplified security requirements for the site. Shang is working with managers at DOE plants where nuclear material must be protected to help them plan for a more efficient yet more secure site.

In addition, the Livermore model incorporates DOE and federal policy directives. If managers run a simulation to consider the effects of building a new facility, construction outlays would increase, as expected. However, the model would also show increased spending for demolition and decontamination because DOE policy states that one square foot of old facilities must be removed for every square foot of new construction.

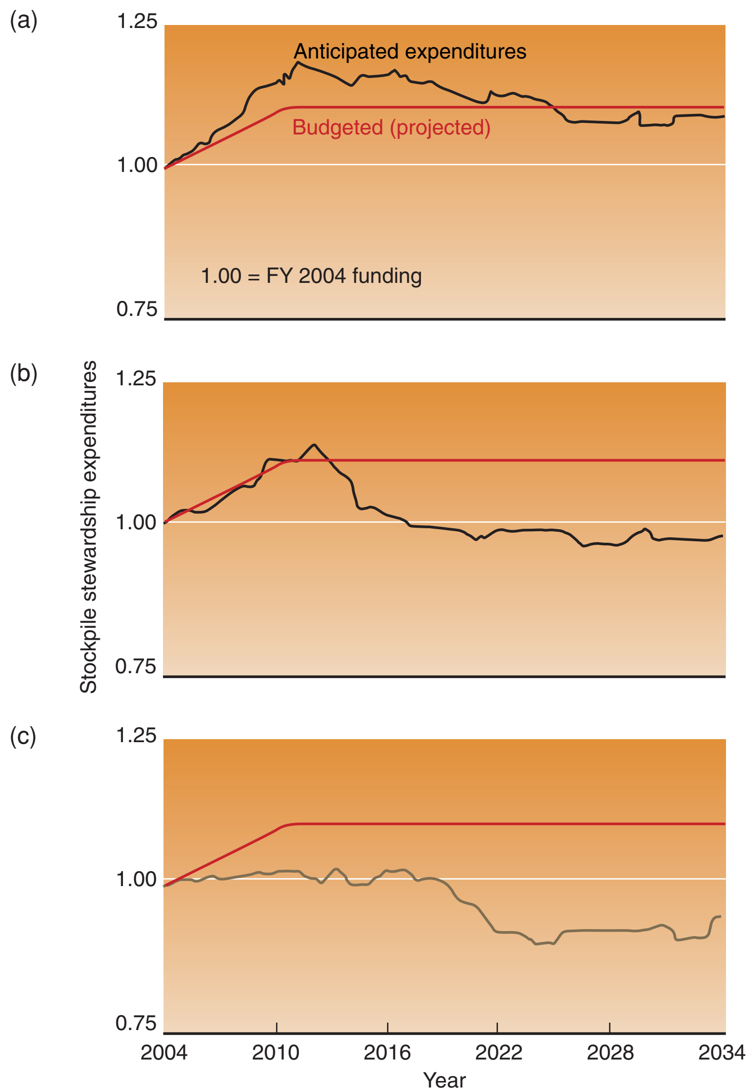
Designed for portability and extensibility, the model can be modified easily and the results viewed almost instantaneously on a desktop computer. Effects can be calculated out to two decades or more. Users can also back-calculate 10 to 15 years to test the effects of strategies considered in the past.

Shang notes that many businesses use complex models to determine the likely effects of strategic decisions. Similar models have been used to examine ways to improve U.S. health-care delivery and foresee how the nation would respond to an influenza pandemic.

Work Started in 2004

Work on the Livermore model began in April 2004. At that time, Vic Reis, former assistant secretary for DOE Defense Programs and currently a consultant in the office of the Secretary of Energy, asked the Laboratory to help develop a method to evaluate options for transforming the nuclear enterprise. Reis met with Shang and other managers to sketch out how the nuclear weapons complex works in terms of governing equations. "I was anxious to get it started," says Reis. "Cliff started from scratch, and we stayed in contact for six to eight months."

Shang used system dynamics software to write a set of interlinking differential equations that describe the operations of the complex. Various Laboratory



The Livermore model shows how proposed changes to the nuclear weapons infrastructure will affect expenditures for stockpile stewardship. (a) The projected budget will not accommodate all of the proposed plans (new facilities, programs, and weapon dismantlement) in the first option. (b) The second option, which includes consolidating nuclear material storage at NNSA facilities, reduces anticipated expenditures. (c) The third option significantly reduces expenditures by implementing such programs as the Reliable Replacement Warhead Program.

Members of the model development team include (from left to right): Chris Brannan, Jeene Villanueva, Sharon Beall, Pauline Gu, Pat Sholl, and Cliff Shang, team lead.

The Livermore model can access a large database with current information on NNSA's budget; the nation's nuclear weapons stockpile, including refurbishment plans and maintenance activities; recapitalization, demolition, and decontamination schedules; construction data, including comprehensive site plans; and program execution data, such as research and development capabilities and production capacity.

experts contributed to the project, including a computational biologist, computer scientist, systems analyst, political scientist, budget analyst, and facility manager. The model's governing equations, similar to those called Lotka–Volterra equations, were originally developed to describe the dynamics of biological populations in which two species, such as predator and prey, interact. (Formulated independently by scientists Alfred Lotka and Vito Volterra in the 1920s, Lotka–Volterra equations are used to model ecological, social, and economic phenomena as well as chemical reactions and nucleosynthesis.)

To incorporate essential data and make the model as realistic as possible, Shang worked with all NNSA facilities and national laboratories to collect data on the stockpile, NNSA's various facilities, and their capabilities. For example, budget data include current costs and long-term projections for construction, demolition, decontamination, direct and indirect employee payrolls, and related expenses. Data on the Stockpile Stewardship Program describe refurbishment plans, production directives, and master schedules. Research, development, and testing data include details on Lawrence Livermore, Los Alamos, and Sandia national laboratories; the Nevada Test Site; and the production plants at Y-12, Pantex, Sandia, Savannah River, Kansas City, and Los Alamos. With this level of detail, users can drill down to study projects ranging from major facilities to utility upgrades at each site.

"Modeling the entire nuclear enterprise may seem like a daunting task," says Shang "but Livermore people have extensive experience in building simulation codes and modeling complex systems." He notes the toughest evaluators have been other Laboratory managers such as George Miller, associate director at large at Livermore and chairman of the Science and Technology Panel of the Strategic Advisory Group to U.S. Strategic Command (STRATCOM).

High Marks from DoD Agencies

Shang has given presentations to managers at DOE, NNSA, and many NNSA facilities. He has also briefed managers at STRATCOM, the Defense Threat Reduction Agency (DTRA), and the office of the Secretary of Defense. The model earned high marks for thoroughness and utility, and Shang has received requests for specialized versions to help guide military agencies with their planning decisions. “What Cliff has done is remarkable,” says STRATCOM Manager Stan Gooch. “It allows senior managers to see the impacts of policy options and budget decisions.”

STRATCOM and DTRA are collaborating with Livermore experts to develop a complementary model of the DoD enterprise. “Cliff’s model is of great interest not only to DOE but also to DoD,” says Peter Terrill, who leads the DoD Stockpile and Transformation Group. “His work has created an opportunity for a potential decision-making tool that can also incorporate the DoD nuclear infrastructure, which is a critical part of the picture that’s not well understood. As a result, DoD is hopeful that Cliff’s work will help DOE and DoD get a holistic view of the joint nuclear enterprise, which is a critical aspect of the RRW Program.”

One of the model’s most useful applications is examining the ramifications of dismantling nuclear warheads. The U.S. currently has a large number of warheads in storage, many of them awaiting dismantlement. Although officials are working to reduce the backlog, NNSA does not have the integral capacity in facilities, budget, or personnel to accommodate warhead dismantlement

Toward a Sustainable Stockpile

Military and policy analysts agree that the nuclear enterprise of the future should be safe and secure, affordable, and more responsive to change. The current stockpile consists of warheads developed during the Cold War, when the nation’s defense policy focused on the military might of the Soviet Union and Warsaw Pact nations. These warheads are designed to meet high performance criteria, including a high yield-to-weight ratio, but they are often difficult and costly to maintain and certify without nuclear testing.

Current plans are to maintain a stockpile of 1980s-produced warheads until about 2040. Some experts believe these plans strain the nuclear weapons production and certification infrastructure, making the nation ill-prepared to respond quickly to problems or changes in requirements. Although the plans preserve the nuclear weapons deterrent, a “ponderous and expensive enterprise [is] required to support old technology,” according to *Sustaining the Nuclear Enterprise—A New Approach*, which was written by scientists at Lawrence Livermore, Los Alamos, and Sandia national laboratories.

NNSA Administrator Linton Brooks cautions that the current stockpile was not designed for longevity. “Today, our aging nuclear weapons are being rebuilt in life extension programs that are both difficult and costly. Decisions made during the Cold War forced the use of certain hazardous materials that, in today’s health and safety culture, cause warheads to be much more costly to remanufacture. Maintaining the capability to produce these materials causes the supporting infrastructure to be larger and more complex than it might otherwise be.” He notes that small changes have been implemented over many decades, and stockpile warheads continue to evolve away from the designs originally tested underground at the Nevada Test Site. “The result is increasing uncertainty in the long-term reliability of warheads,” says Brooks.

Science-based stockpile stewardship, the nation’s program to keep the nuclear stockpile safe and reliable, has worked since its inception 10 years ago. Stockpile warheads have a documented nuclear test history, they are subjected to extensive surveillance, and issues have been addressed based on the results from nonnuclear experiments and advanced simulations. NNSA managers believe that a better long-term approach for a sustainable enterprise is to shift from a program of warhead refurbishment to one of warhead replacement.

To better evaluate this proposal, NNSA began the Reliable Replacement Warhead (RRW) Program. The goal of this program is to determine the effectiveness of replacing existing warheads with ones manufactured from materials that are more readily available and more environmentally benign than those used in current designs. Such changes would require that Cold War design constraints, which drove tight performance margins, be relaxed. These modified warheads would be much less costly to manufacture, their designs would include advanced safety technology, and their safety and reliability would be easier to certify. The proposed warheads could thus help NNSA achieve the goal of a more affordable, sustainable, and responsive nuclear enterprise.

Until the nation achieves a responsive infrastructure, it must retain a substantial number of nondeployed warheads to hedge against a technical failure of a critical warhead or delivery system or against an unforeseen threat. Establishing a responsive nuclear infrastructure, together with the RRW Program, would make possible additional stockpile reductions.

Says Brooks, “Success in realizing our vision for transformation will enable us to achieve over the long term a smaller stockpile, one that is safer and more secure, one that offers a reduced likelihood that we will ever need to test again, one that reduces NNSA and DoD ownership costs for nuclear forces, and one that enables a much more responsive nuclear infrastructure. Most importantly, this effort can go far to ensure a credible deterrent for the 21st century that will reduce the likelihood we will ever have to employ our nuclear capabilities in defense of the nation.”

while conducting its other key stockpile stewardship activities: the Life Extension Program (LEP), which refurbishes selected warheads; the Limited Life Component Exchange, which regularly replaces a few key components; and possibly, the RRW Program.

NNSA managers thus want to examine different levels of effort for the four tasks to determine how each mix would affect the complex. For example, if production begins on RRWs, the dismantlement effort would increase, and LEP activity would decrease. The model can also show how efficiencies in various RRW activities might affect the enterprise. It can then compare those projected expenditures with the life-cycle costs of selected warheads and the savings expected when expensive-to-maintain warheads are retired. The model could also delineate the effects of increased capacity if such a change is warranted.

Incorporates Stewardship Tools

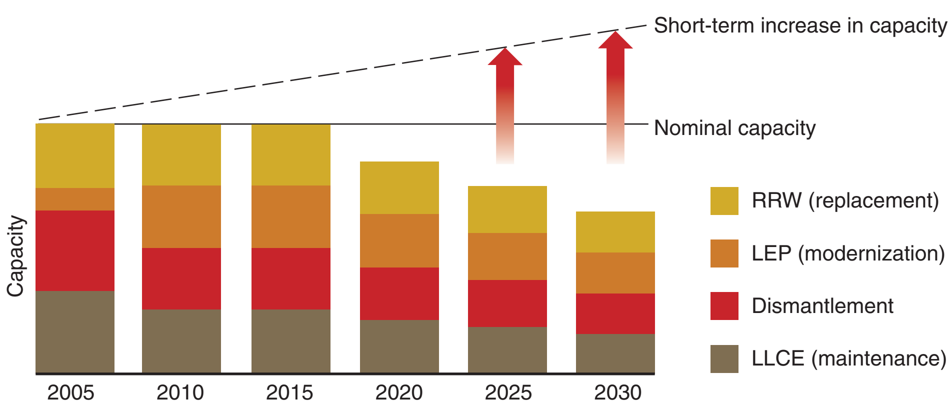
NNSA has many existing and future stockpile stewardship capabilities and facilities that can be used to transform the nuclear enterprise. The Livermore model helps managers determine the best use of those resources, such as the Advanced Simulation and Computing Program's codes and supercomputers, which perform three-dimensional calculations to enhance safety and security; an improved physical properties database; and hydrodynamic, flight, and engineering tests. In addition, new facilities, such as the Dual Axis Radiographic Hydrodynamic Test Facility at Los Alamos and the National Ignition Facility at Livermore, are beginning to make important contributions. The model shows production delays if key facilities are not in use or must operate at reduced capacity. At the same time, it can indicate enhanced confidence in the stockpile as new resources become available and can show how stockpile stewardship tools help guard against technological surprise.

Nuclear weapons experts are working on a more complete model that combines both DoD and NNSA assets, data, and plans. The DoD components will include data on delivery systems, such as intercontinental ballistic missiles, bombers, and submarines, as well as DoD operations, maintenance schedules, and planned acquisitions. "If the President says that because of a changing geopolitical situation, we must revise the nuclear weapons policy, our requirements for both warheads and delivery systems might change," says Shang. "A combined DOE–DoD model will help decision makers determine how the two departments together can meet new or evolving policy directives."

Reis successfully used system dynamics models to help explain the Fiscal Year 2006 Energy Bill as it advanced through Congressional committees. He is developing an even more comprehensive view of the nuclear enterprise that includes the weapons complex and the nuclear power industry. This model will examine the interrelationships between civilian and defense applications of nuclear energy and issues such as climate change and nonproliferation.

The Livermore model will continually be refined, expanded, and tailored to meet new user needs. Livermore physicists believe their modeling expertise, honed on physical systems as large as supernovae and as small as subatomic particles, can help managers plan for a more efficient and responsive nuclear enterprise, one based on a sustainable stockpile.

—Arnie Heller



Representative data show different model scenarios for stockpile stewardship activities, such as the Life Extension Program (LEP), which refurbishes selected warheads; the Limited Life Component Exchange (LLCE), which regularly replaces a few key components; warhead dismantlement; and the proposed Reliable Replacement Warhead (RRW) Program. The model can also project the effects from increasing capacity to respond to an unanticipated threat or a technical problem.

Key Words: Life Extension Program (LEP), Limited Life Component Exchange (LLCE), nuclear enterprise model, Reliable Replacement Warhead (RRW) Program, stockpile stewardship.

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